TEV Separator Helix Review Report Aug 26, 2003

Compiled by H. Edwards 9/22/03

1. Introduction

The upgrade program for the Tevatron separators consists of the five elements listed below (Fig 1).

WBS	Task	In Charge	Labor Est ($K)	Labor Cont	M&S Est ($K)	M&S Cont	Start
1.3.4	Tevatron High Luminosity	V Shiltsev	7,588	51%	5,103	47%	1/1/03
1.3.4.4	Increased Helix Separation	R. Moore	1,222	40%	1,847	27%	4/1/03
1.3.4.4.1	Optimize separation with present Separators	Y. Alexahin	39	60%	0	0%	5/1/03
1.3.4.4.2	Tevatron Polarity Switches for Separators	B. Hanna	98	47%	237	41%	11/3/03
1.3.4.4.3	Long Separators	R. Moore	735	25%	1,570	23%	9/2/03
1.3.4.4.4	Coated Separators	B. Hanna	222	70%	40	100%	5/1/03
1.3.4.4.5	Additional Seperators	B. Hanna	128	60%	0	0%	4/1/03

Fig 1. DoE Review Shiltsev

Background

The present hardware configuration is given by Johnstone in Fig 2. In Fig. 3 he gives the configuration with additional arc modules. Fig. 4 discusses the possible lengthening of the separators near the IRs. Fig. 5 gives an estimate of improvements based on four types of improvements to the helix orbits: a) higher separator operating voltage, b) crossing angle at the IP, c) additional arc modules, d) added length to the separators at the IR regions. Fig. 6 gives the figures of merit used by Alexahin and Johnstone. Fig. 7 and 8, respectively give Sen's list of needed studies, and his conclusions on beam beam effects from the studies to date. (Section 6 of Figures is near end of this report.)

Organization of this report-

The two external reviewers, Rubin and Sinclair, have provided thoughtful reports, each in their areas of expertise. Rubin speaks to the beam operation with separators; Sinclair, to the separator high voltage technology. These reports in Section 5 below are of particular value in this review.

Section 2 makes comments about the lack of concise understanding of the role of the beam beam interaction, its effect on operation and possible mitigation by larger helix amplitudes. Here, Syphers has provided a description of the present understanding and status of the ongoing accelerator physics work to understand the role of the beam beam effects on the operation of the Tevatron. Clearly this is a very complex problem to understand.

Sections 3 gives a summary of the major recommendations addressing the main issues of the review, and Section 4 gives further recommendations and comments.

Section 6 includes some of the summary transparencies from the presentations.

2. General comments-

There is no clear evidence that implementing additional and stronger separators will lead to better operation. At injection energy the machine aperture limits the amplitude of the helix. During acceleration up to ~500 Mev there is sufficient separator strength to keep the amplitude of the helix, as measured in nominal beam sigma, constant. Above this energy the helix shrinks from about 6 sigma to about 3.5 sigma (Alexahin). A new solution is presently under implementation that would bring this opening to more like 5 sigma (Alexahin). Losses up the ramp, during squeeze to low beta, and detector backgrounds during storage are the main issues. There is little evidence that luminosity lifetime at present luminosities is limited by the helix.

All this is not to say that larger helix openings and smoother radial separation will not help especially as intensities increase. But rather, the evidence is weak and a clear indication of the most relevant effects was not given.

Diagnostics

It is clear that studies and tuneup of the helixes are very difficult. This is made more difficult by lack of (or lack of trust in) fundamental beam diagnostics, like beam position, tune, chromaticity, coupling, and determination of orbit betas and dispersions. The comment was made by Alexahin that these properties seem to not be stable. Believing and understanding the orbit and changes to the orbit and optics apparently are a continuous problem. (At another meeting it was also mentioned that coupling up the ramp could no longer be measured though an adequate tool existed prior to a year ago. Such a tool needs to be resurrected or a new one implemented.)

Rubin in his report speaks clearly to the importance of the optics tools and of identifying sources of optics instability. Much work is being undertaken to improve the diagnostics and it is important to understand their present status and schedule for improvement relative to the needs of helix improvement studies so that appropriate priorities can be assigned.

The figure of merit-

The main figure of merit that is being used as a design tool is the average spacing of the long range crossings normalized to nominal beam sigma. Two slightly different definitions are used by the two people working on new helix orbits (Fig. 6), resulting in different numerical values of figure of merit.. It would be good if these could be reconciled (and ambiguities of rms vs 95% emittance clarified).

More importantly however is- What is the best figure of merit for the separation? Is it long range beam beam tune shift, resonance driving terms or both? Is just a straight average over bunch crossings of the normalized spacing the best criteria, or are the smaller crossings more important than just by the weighting given in a linear average? What is the best way to add the impacts from the various crossings? Is smoothness important? (Rubin and Syphers suggest it is.) Should the beam size include the momentum term or not? What is the roll of longitudinal emittance and synchrotron oscillations? How does one expect the different effects to scale with energy and acceleration? Johnstone pointed out that the betatron beam size scales as $E^{-0.5}$, and momentum size as $E^{-0.75}$ (what about during acceleration?), where as the separation for constant voltage scales as E^{-1}. But how is the beam beam force expected to scale as the energy increases? All this may be well understood by the people working the problem but it was not presented to the committee clearly.

All this is part of the question- Are larger helixes actually expected to help, and why? How can we find out? And what is a study program that could pin down in a systematic way the various dynamics drivers? What is the prioritized list of needed diagnostics?

Comments from Syphers on the status of understanding the role of beam beam forces.

The long-range beam-beam interactions occurring along the helical orbits produce a large spread of tunes among the 12 bunches in a train due to the different orientations of the interactions for each bunch. It was presumed that the effect on the dynamic aperture due to the nonlinear quality of the long-range force would also be directly related to the beam separation, and hence directly related to the long-range tune shifts. Dynamic aperture calculations by Sen, et al., have shown this not to be the case. It is clear that the dynamic aperture is more closely related to the resonance driving terms generated by the distribution of interactions. Hence, while a particular helical orbit may in fact produce a larger average beam separation in units of rms transverse beam size, it may be possible for this orbit to have larger resonance driving terms and smaller dynamic aperture.

The separation of the beams at injection is limited by physical space and dynamical aperture caused by the nonlinear fields within the Tevatron magnets due to persistent currents. As the beam is accelerated, adiabatic shrinking of the betatron and momentum oscillations makes the beam smaller while at the same time the persistent current nonlinearities in the magnets are reduced. Thus, at collision energy the beams in principle can be separated further, especially in units of their rms transverse dimensions. As presented by Sen, the beam-beam effects do not appear to be limiting the particle lifetime at 980 GeV as they do at 150 GeV. It was shown, however, that particle loss at 980 GeV is exhibited during the low-beta squeeze, during which the helical orbits are adjusted as the optics of the Tevatron are altered, to the point where the beams are momentarily brought close together.

Bearing these issues in mind, the work presented by Alexahin addresses the reduction of resonance driving terms through alterations of the helix. He has shown how progress can be made at injection and through the Tevatron ramp to reduce losses and improve beam lifetime using existing separators. The figure of merit in his analysis of important resonance driving terms is the beam separation in units of rms betatron oscillation amplitude. Meanwhile, the work presented by Johnstone was addressing the helical orbits at full energy. Here, the nonlinearities of the Tevatron dipole magnetic field are reduced, especially on the scale of the reduced beam size. Johnstone showed how the present separators, with polarity reversal switches on each, can be used to generate a smoother transition of the helix through the low-beta squeeze in order to maintain a more favorable beam separation throughout the entire process. For his figure of merit, he looked at the separation of the two helical orbits in units of the total rms transverse size of the proton beam, including the momentum contribution. Improvements to the helix during the squeeze were made earlier in Run II by Alexahin, but were limited by the small number of separators which presently have reversal switches.

For reference, a proton beam with a 95% normalized emittance of 20 pi, and 95% longitudinal emittance of 4 eV-sec, at a location where the amplitude function is 100 m and the dispersion function is 4 m, will have transverse rms beam sizes given by:

@ 150 GeV:	betatron - 1.4 mm	dispersion - 2.0 mm	total - 2.4
@ 980 GeV:	betatron - 0.5 mm	dispersion - 0.5 mm	total - 0.7

The roll of momentum spread and synchrotron oscillations on the beam lifetime in the presence of beam-beam interactions was not explicitly addressed in the review. The above considerations lead to several important questions -- Will larger helical orbits actually help, and why? How can this be resolved? What study program can pin down in a systematic way the various dynamic drivers? What is the prioritized list of necessary diagnostics?

3. Summary of major recommendations-

1) Provide polarity switches for all separator systems including those to be installed. Explore buying commercial switches. This could save considerable expense and effort. (See Sinclair comments). Having switches on all systems will make it possible to explore pbar helixes with the proton beam. This is important for setting up any new helix tunes.
2) Finish fabrication and processing of the eight additional separators that exist. Electrical power supplies and controls should be obtained. Install six in the arcs. (See Fig 3.) This should allow for smother helix orbits. (See Rubin comments.)
3) Explore studies and operation of present separators at higher voltage. The separators have been processed at 130 KV/plate, but are operated at 106 KV max during stores. Determine if a performance advantage can be achieved and if sparking will indeed be a problem. Separators may be processed during times when tunnel is closed but no beam in TEV, e.g. during quench recovery. Also perform proton studies using steering magnets to augment separator strength to determine single beam dynamic aperture limitations. (See Rubin comments.)
4) Do not initiate R&D on glass coated separators. (The proposed study would be done in a short tank with rather different geometry than used for the separators.)
   Rather initiate an improvement program on the present separator performance and processing time. A 30% gain in operating voltage does not seem out of

the question. One of the spare units could be used for study.(See Sinclair comments)

- Understand limitations of present separators and ancillary equipment. (We learned that 180KV had been attempted for a short time and a feedthrough had been a problem.) Improve where necessary.
- Implement clean dust free water, air, and handling procedures, and parts cleaning and vacuum procedures that use filtered nitrogen from liquid boil off and other UHV procedures. (e.g. degreasing and particle count monitoring)
- Develop better and more specific fabrication, assembly procedures and quality control.
- Review present plate manufacturing and polishing procedures and specifications. Assure that polishing is done with appropriate agent.
- Review the field quality produced by the ideal design separator geometry and how flatness specifications affect the quality. Determine if higher order (quad and higher) separator fields can affect the beam operation. Determine what a tolerance specification should be and how plates might be paired to optimize field quality. (Finley, Sinclair)
- Try different separator plate fabrication and polishing like electropolishing of stainless and Ti plates. (See specific comment by Sinclair on stainless material.

5) Do not at this time undertake plans for fabrication of 12 24 inch longer separators for the IR regions. Rather work on increasing the operation voltage of the present design.
   Evaluate the benefits of four additional separators that could fill the 73" potentially available space on either side of each IR. Horizontal or vertical pairs of these could be installed. The resulting helix might be elliptical, but would reduce time and expense relative to twelve units.
   Any proposal to use the 73" plus space by removing Q1's or BPM's, etc would need an impact evaluation both of hardware and beam operation. Would it preclude 25cm beta*?

4. Other recommendations and comments -

6) Study and if necessary repair any bad effects that may have resulted from disconnecting correctors from their original circuits when implementing "differential correctors". Martins described the "differential correction" coil scheme. Correction magnets had been removed from other circuits in order to use them in these circuits. As removing correctors from specialized circuits could result in undesirable resonant driving terms a study should be carried out of the potential effects.
   If possible these corrector should be put back in their original circuits, possibly by summing currents needed for the two different correction circuits.
7) Bunch schemes of 18x18 (or other numerology that avoids close IR near neighbor interactions.
   There is considerable uncertainty as to whether near neighbor crossings in the IR region with very small separation in mm (but reasonable in terms of beam

sigma) are a factor in beam performance. These crossings apparently produce most of the (5th and 7th) resonance driving terms.

Studies should be initiated with high priority that remove certain proton bunches so that pbar bunches that do not see these near collisions can be compared with those that do.

In addition a plan should be developed as to just how 18x18 operation could be carried out. This plan would need to evaluate impact on all accelerators in the chain, especially pbars from the source and how to get 2xNpbar per bunch. If feasible 18x18 could be run with the same luminosity as 36x36, but with half the beam beam and no near neighbors. To many interactions per crossing in the detectors should not be a problem for some time.

18x18 operation was a recommendation of the DOE Review.

8) Studies- Sen provided a study list (Fig. 7) that should be reviewed and integrated with high priority into the study program. It is clear that well planned out and executed studies are key to setting up optimal helixes and understanding the relevant parameters. A well instrumented and stable machine is also a prerequisite. (See Rubin and overall comments.)
9) A crossing angle at the IP was suggested by Johnstone as a way of separating the near neighbor bunches. Such a scheme makes for added complexity of understanding the beams and was not supported by the review committee. (See Rubin.)
10) The A0 straight section- The A0 straight section has a high beta design, a hold over from fixed target optics. It is not clear if this region has real impact on the operation but it does appear to be an aperture restriction. There may be advantage in reconfiguring it like other straight sections, and it certainly would be good housekeeping. But it will be considerable work. Just what would need to be done should be documented. We heard that the F48 bypass (with electron lens fittings) would need to be rebuilt, or a number of magnets moved. We favor a solution that does not move magnets, and note that removing Q1's will also require bypass modification.
11) D0 Roman Pots- The D0 Roman pots and the desires of the experimenters require that there is a sign reversal of the helix between injection and storage. This has been a problem in the past, but currently is not. Future helix solution investigations should not be constrained by this limitation. If more separator space is required near the IRs, these pots will need to come out in any case.

5. Reports from Rubin and Sinclair

A) D. Rubin September 1, 2003

Tevatron Helix Review August 26, 2003

1. Observations

Amplitude of the separation helix is limited by physical and/or nonlinear aperture at 150GeV where separators are most effective and dipole field quality is compromised. Alexahin's Figure 6 suggests that pbar lifetime is only slightly effected by the presence of the proton beam at 150GeV before the start of the ramp. Indeed proton lifetime seems to be slightly lower than pbar lifetime, and I conclude that the pbar lifetime is determined by guide field nonlinearity rather than by parasitic interaction with the more intense proton beam. The plot indicates that the lifetime of both beams deteriorates during the ramp but that the pbar lifetime is considerably worse than the proton lifetime, evidently due to beam beam effects. And the pbar lifetime seems to get worse during the latter part of the ramp, E>500GeV.

2. Suggested Measurements

1. Lifetime of protons from injection energy, through ramp to low beta, with helix opened. Presumably the lifetime for pbars cannot be any better than this, even if helix separation were perfect.
2. Lifetime of pbar from injection energy, through ramp to low beta. This should give the same result as for protons, except for differences in beam emittances. If not perhaps there is some other asymmetry.
3. Measure lifetime from injection energy through ramp to low beta, using dipole correctors to simulate more voltage on the separators. Before investing energy in stronger separators it would be good to know that the Tevatron acceptance is big enough to exploit them.
4. Many of the measurements are simplified if all separators can operate at either polarity.

3. 18 or 27 bunches/beam vs 36

The luminosity

$$L \sim n_{bunches} N_p N_{pbar}$$

where $n_{bunches}$ is the number of bunches per beam and N_p and N_{pbar} are the numbers of protons and antiprotons in each bunch. Then, as explained by Tenaji Sen, if the number of bunches is reduced, and the number of pbars increased to maintain total pbar current, luminosity is unchanged. But with fewer proton bunches, parasitic effects are reduced as well. Assuming that the injector can deliver a suitable pbar beam, this seems a promising direction. If the number of interactions/crossing is too high with 18 bunches/beam, then perhaps 27 bunches/beam would be a possible compromise.

4. Helix optimization

An important ingredient in CESR lattice design is optimization of the “pretzel” efficiency. Efficiency is defined as the ratio of the minimum parasitic separation to the maximum closed orbit displacement and corresponds roughly to the “smoothness” of the Tevatron helix. In CESR there are only 4 horizontal separators and manipulation of separator voltages is of limited benefit, but all CESR quadrupoles are independently powered and pretzel efficiency is tuned by adjustment of phase advance between separators, and from separators to crossing points. The parameters available for Tevatron helix optimization are the separator voltages, rather than betatron phase, but in either event the figure of merit is the same. Since large helix amplitudes force the closed orbit into regions with poorer field quality, and exacerbate effects of sextupole feeddown, a smooth helix is critical. Johnstone showed that with the existing compliment of separators, that the quality of the helix could be significantly improved and that with the installation of the now “spare” separators that it could be made even better. I believe that the improved helix should be implemented as soon as possible, and the additional separators made ready and installed.

5. Sextupole feed down

In CESR “knobs” are designed to adjust the sextupole distribution to compensate for feed down. The design preserves chromaticity so that it is possible to change differential tune and coupling without changing chromaticity. Perhaps it is possible to do something similar through the Tevatron control system. Sextupoles that have been removed from the chromatic correction circuit should be run so that when the feed down compensation is turned off, the sextupole current corresponds to that in the circuit from which it has been removed, thereby minimizing the distorting effects of the compensation. Also, the effect of the feed down compensating sextupoles should be measured to be sure they are performing as intended.

6. Crossing angle

In a crossing angle configuration, beams are displaced differentially in the interaction region quadrupoles. Bunches are very closely spaced in CESR. The first parasitic crossing as 2.1 m from the interaction point and separation depends on the existence of a crossing angle. But the resulting large displacement of the beams in the very strong final focus quadrupoles, and the lack of a direct method for determining the relative displacement of the beams at the interaction point significantly complicates operation. Although we have operated CESR with a crossing angle for a decade, we continue to find it necessary to develop new diagnostics to untangle details of beam characteristics at and near the IP. In view of that experience, I would recommend against implementation of a crossing angle in the Tevatron without very detailed evaluation.

7. Orbit correction

Implementation of any change in the helix, such as by smoothing or overall amplitude, will be complicated by physical and nonlinear aperture and by feed down effects. Rapid progress depends on good diagnostics and the ability to measure trajectories is perhaps the most basic. It is absolutely essential that the BPM system specify the closed orbit with respect to the center of the aperture, and development of the requisite instrumentation should have the highest priority.

Sensitivity to orbit drift is enhanced in the open helix configuration, and orbit differences should be analyzed to identify moving quadrupoles or unstable power supplies.

8. Lattice functions

Optimization of the helix and interpretation of feed down effects depends on understanding of the linear lattice functions. If the lattice functions are significantly different from the design values, and/or are changing in time, implementation of a new helix will be much more difficult. Again, it is very important to be able to measure lattice functions and to establish the stability of the lattice.

9. Separators

It is not clear that separator voltage is limiting Tevatron performance. Furthermore, the limiting separator voltage is not well established. The evidence suggests that the separators might operate at significantly higher voltage if they were conditioned to a voltage that is beyond the capacity of the existing feedthroughs and/or power supplies. The 150kV to which the separators are traditionally processed seems somewhat arbitrary and there is no obvious reason to suppose that the existing plate design is incompatible with 180kV or 200kV. This should be explored before undertaking R&D on alternatives that will have a long development time.

10. Summary of recommendations

The following is a roughly prioritized list

1. Implement new BPM system for reliable orbit measurement
2. Machine studies as noted above and all of the measurements enumerated by Tenaji Sen. Install polarity reversal switches on all separators.
3. Optimize helix smoothness through ramp to low beta with existing complement of separators

4. Install 6 additional “spare” separators and further improve helix smoothness
5. Operate with fewer, but higher intensity pbar bunches.
6. Improve implementation of feed down correction sextupoles
7. Identify sources of orbit and beta drift
8. Modify A0 optics to reduce beta
9. Experiment with higher separator voltages.
10. Determine conditioning limit of existing separators.

B) Sinclair Remarks from the Helix/Separator Project Review

Fermilab, August 26, 2003

Separators

In several places, we received incomplete or inconsistent information. For example, we were told that the polishing of the separator plates was done with emery cloth or with alumina paper. Before this review, Curtis Crawford (presently at Cornell) told me that polishing of the original separator plates was done with scotchbrite. I don't know which of the answer(s) is the actual one, and perhaps more than one method was used. However, both emery cloth and scotchbrite are completely unsuitable for polishing high voltage or high field strength electrodes – at any stage in the process.

At one point, a presenter (Hanna) stated that it was possible to observe visible dust on the separator plates. This statement was subsequently said by someone else to be not the case. It should be determined whether or not this statement is correct. If visible dust is observed, one should probably, at an opportune moment, look into a separator installed on the Tevatron (perhaps one operated at the highest fields) to see if dust is observable. If dust is in fact observed, it may be advisable to clean the plates, particularly before attempting operation at even higher fields. It may be possible to do this without disassembling the separator by, for example, adapting the technique for cleaning laser mirrors to the much larger area of the separator plates.

We were told in a presentation (Bossert) that the polished surface finish on the separator plates was 4-8 microinches. Someone from the audience said that it was in fact a 2 microinch finish. I am very skeptical about either of these numbers. One microinch is 25 nm, so even an 8 microinch finish would correspond to 200 nm. This is pretty spectacular for metal polished by hand. I have polished a large number of electrodes over the years, and typically a 1 microm finish is the best obtained. Reaching this level of finish requires very careful hand polishing with 1 microm diamond paste. Well before this finish level is reached, a stainless steel piece will look "beautiful" – with a brilliant, mirror-like surface. The photos we were shown of the electrodes were very far from such a finish – they were in fact not even close to mirror-like. There may be a specification for a 4-8 microinch finish, or even 2 microinch finish, but I very much doubt that even an 8 microinch level was ever in fact closely approached.

We were given no information on the specification of the stainless steel used for the plates. Poor quality material could very well be the source of serious problems at the relatively modest fields of the separators. For example, dielectric inclusions and/or "stringers" can be the source of significant field emission and/or breakdown at fairly low fields, and these imperfections are common in stainless as a result of the manufacturing processes employed. It might be useful to talk with a knowledgeable metallurgist about the proper specification of the stainless. If material problems are present, they will only be worse at the planned higher fields.

From the pictures provided (Bossert's slides 4, 6, 7, 8, 9, and the drawings on page 12 of the Specification # 5520-TR-333689) it was not clear how well the triple junctions on the ceramic insulators are protected. Emission from triple junctions is a well-understood source of surface flashover on ceramic insulators. Someone should look at the actual dimensions and determine the electric field strength at the triple junctions. If there are any doubts, a quick run or two with POISSON would answer the question. This may become more important as the separator voltages are increased. It does appear that if the triple junctions are not adequately shielded, it should be a simple matter to fix the problem. Since the separators have to operate with both polarities, both the triple junctions on each insulator need to be well shielded.

The mechanical tolerances appropriate for the separator electrodes and their mounting are not well developed. The only number provided was 0.080 inches, thought is was not clear what this number meant. It was stated (Hanna) that straightness had been a problem with the electrodes in the past. It should be practical to develop a set of tolerances for the individual electrodes, their mounting, and the transfer of the information on the mounting to the outside of the vacuum vessel to allow correct alignment, all based on the required performance in the machine. It was pointed out (Finley) that there may be unacceptable non-linearities in the separator field over the 5 cm square physical aperture. This, too, should be examined quantitatively.

It is not clear from the information provided that the processes used in assembling the separators (Bossert's slides 12, 15,16) are appropriate to achieve the required separator performance. Steps such as "white glove" inspection, "any necessary hand polishing", etc. need to be better quantified. If indeed "distilled" water is used, one should switch to high quality DI water. Similarly, "nitrogen" should be from liquid nitrogen boil-off, filtered if necessary. Protective bagging should be done with two bags as is standard in ultrahigh vacuum work – an inner nylon bag to minimize particulate contamination, and an outer polyethylene bag to provide a robust sealed environment.

The total labor involved in construction of a separator seemed excessive to me. The actual parts count is not all that large. I note that two weeks are devoted to "Pre-Assy Leak Check" of the vacuum vessel. I compare this to the leak check of the vacuum vessels for either the JLab cryomodules or the SNS cryomodules. These latter vessels have far more penetrations and far more welded joints than the separator vessel, and thus are correspondingly more involved to leak check, yet this requires less than two days for a two-person crew. Developing electropolishing for the separator electrodes could easily result in a superior product with far less labor involved. Similarly, it should be possible to reduce the time/labor for the cleaning operations significantly below the quoted two man-weeks (for presumably two people). There should be established criteria for steps such as polishing the shells (in fact, I wonder how one polishes the inside of a 100 inch long, 12 inch diameter vessel at all). Overall, I believe it should be possible to substantially reduce the labor involved in producing a separator by carefully defining the steps, providing well-justified quantitative criteria for these steps, assuring proper tools and processes are used, etc.

I reviewed the separator assembly traveler (Specification # 5520-TR-333689), which is surely in draft form. This still needs a considerable amount of work in a number of places. For example, the 300 C bakeout (step 11.7, page 28) simply states "turn the separator temperature up to 300 degrees C"! Has anyone thought about the time it takes for the inside components, which are thermally well insulated, to come up to temperature, while the outer vessel grows over half an inch in length? Is there no control over the rate of rise of temperature (other than the thermal mass of the system)? The instructions for tightening the bolts on large flanges on an ultrahigh vacuum vessel (step 9.3, page 26) are incorrect. Generally, the descriptions of steps to assure ultrahigh vacuum cleanliness or high voltage performance (e.g. step 5.10, page 13, step 9.3, page 26) do not indicate a good understanding of the problems.

It was stated that separator sparks, when they occur, are not in general in the separators operating at the highest voltages. This might indicate a problem with electrode or insulator cleanliness, high voltage feedthroughs, ceramic insulators, etc. It is not easy to diagnose which component might be failing. Often a "spark" can induce signals on other devices nearby, leading to possible misinterpretations. In my experience, before a high field electrode actually sparks, it shows small, unstable, measurable emission currents (n.b. I have dealt almost entirely with electrodes that are biased negative). We have had success at JLab in measuring these currents with small, inexpensive, home-built picoammeters. These are protected from damage in spark events with Zener diodes, and are mounted in the atmosphere directly at the high voltage terminal. They are battery powered, and communicate either optically (at the highest voltages) or over a fiber-optic link (at 100 kV). Something like this might be useful as a monitor to warn of an impending problem at high voltage. At the present time, there is no way at all to determine if any separator plate is drawing a small current, and the power supply current is completely dominated by the 20-30 Mohm shunt resistors.

There is a very good way to terminate high voltage cables and make high voltage cable connections, developed by Raychem. This is widely used in the electric power transmission business. While Raychem will not warrant their materials at the voltages we use, I have used them up to 500 kV DC without any problems, for many years. Basically, their system is a combination of a silicone dielectric "goo" and a high resistance shrinkable tubing. One simply strips off the outer conductor of the coaxial cable carrying the high voltage for an appropriate length, cleans the exposed inner insulator, applies a suitable amount of the dielectric "goo" to the inner insulator, and shrinks the high resistance tubing from the braid end of the exposed center insulator to the high voltage conductor end, squeezing the "goo" forward, toward the exposed center conductor end, as you shrink. The finished result is a void-free central dielectric with a high, uniform resistance connecting the outer braid to the inner conductor, grading the potential uniformly along the way. It works very, very well. I have never had a failure of this scheme in a number of applications. I can provide you with information on the Raychem materials if you don't have a Raychem rep in your area.

We heard from Romanov about possibilities for significantly increasing the voltage on the separators, by using electrode materials other than stainless steel. He mentioned glass plate separators. These have been operated at quite high field strengths and voltages as elements of electrostatically separated particle beam lines for bubble chambers. Romanov noted that their voltage hold-off was enhanced by running them at pressures of 10^{-3} to 10^{-4} torr – which is unsuitable for the Tevatron application. Questions about possible charging of the glass, resistive wall instabilities, etc. also were mentioned. Overall, I would not recommend starting down the path of R&D on glass electrodes.

Suitable dielectric coatings on metal electrodes are known to greatly improve their high voltage performance. Adhesion of coatings applied to finished electrodes at high field strength can be a problem. Romanov suggested using an aluminum electrode since it naturally has an oxide coating. However, there is much experience showing that aluminum does not perform well as a high voltage electrode. Hanna stated in his talk that they were "beginning tests on two new electrode materials – glass and aluminum", and that the tank for these tests was presently being baked at 300 C. It was not obvious that anyone else was supporting this work as a way to improve separator performance. It is difficult to support spending time with aluminum, given the record of experience of others.

Personally, I am confident that it is practical to meet the requirements for the separator performance, even at the higher voltages discussed, with stainless steel electrodes, possibly with improved high voltage feedthroughs. It is important to note that the fields required are quite modest – about 4 MV/m at present, and a bit over 6 MV/m with the proposed increases. Given these relatively low fields strengths, it is far from obvious that lengthening the separators in a few locations by a maximum of about 20%, with all the required engineering, tooling, and assembly area changes, is wiser than simply learning how to operate with 20% higher voltage. I believe that electro-polishing, as opposed to mechanical polishing, should be pursued as a possible way to improve performance and reduce labor, and possibly manufacturing, costs. If it is decided to pursue R&D on a new material to obtain better performance, I would strongly recommend titanium. I have obtained much better performance from large area titanium electrodes at high field strength than from stainless steel. Titanium is much lighter than stainless, and is much easier to mechanically polish. If I were starting from the beginning, I would choose to make titanium electrodes. However, I am confident that at the required field strengths, you can succeed with stainless. If you are going to procure more electrodes, it might be interesting to talk to the vendor about doing the job with titanium, as opposed to stainless. The Ti6Al4V alloy is suitable. I also believe that the statement that there is only one vendor for these electrodes is nonsense.

It was stated in Hanna's presentation that conditioning required up to several months per separator! This seems exceptionally excessive to me. For example, the highest voltage guns I have built have a total area at high field strength about 10% of the high field area of the separator plate. We condition these guns to field strengths about a factor of two above those in the separators (Our highest fields are a factor of three higher). This process can take as much as 2 to 3 8-hour shifts. It is common for us to see no conditioning activity at all up to fields as low as 4 MV/m, and not uncommon to see no activity at 6 MV/m. No details of the conditioning procedures followed, or of the results obtained from "good" and "bad" conditioning experiences, were presented, so it is not possible to make any more detailed comments. No details on how conditioning is to be conducted or monitored are given in the specification # 5520-TR-333689. It should be noted that conditioning times of months per separator imply that it could easily require a year or more to condition the additional 6-8 separators planned.

I believe that if a separator requires even a couple weeks to reach stable operation at full field, there is something very seriously wrong, and that it is more profitable to pursue understanding and correcting the problem at that point, rather than trying to continue conditioning. While long conditioning times are likely a result of problems with the electrodes themselves, if there are doubts about either the high voltage terminations/connections or the ceramic insulators, these could be easily tested or pre-qualified (at likely much higher voltages) in separate, dedicated, small test setups, before installation on the separator. Such pre-qualification might prove valuable in general for these components, particularly as the separator voltages are increased. If the conditioning problems are clearly associated with the electrodes themselves, it may be profitable to introduce a gas like dry nitrogen (from liquid boil-off, filtered as necessary) to a pressure of ~ 10^{-6} mbar and continuing to condition. Ions produced in this gas back bombard electron emission sites, which may help to reduce the emission. While this is in some sense a "last ditch" measure, it may be worth trying before disassembling a separator for inspection and re-work of the electrodes.

Finally, I did check the standards in the microwave power tube industry for voltage holdoff in vacuum gaps. A 5 cm vacuum gap should support between 500 and 550 kV with suitable "clean" electrode preparation procedures. (The working limit for electrodes in microwave power tubes is lower, due to the long term deposition of barium on the electrodes.) I believe it is reasonable to expect separators operating at 150 kV per plate (300 kV across 5 cm) to perform acceptably with the low spark rate requirement at the Tevatron.

It was noted that following Tevatron quenches, there is often a several hour window of opportunity when the separators could be operated at any voltage without impact. Doing so might identify separators that would operate reliably at the highest voltages, and others that had problems. This seems very worthwhile looking in to.

Last but not least, there are a number of places to consult to gain information on designing, building, conditioning, and operating devices like the separators. Latham's book "High Voltage Vacuum Insulation – The Physical Basis" is a good general reference. (It would keep you away from trying aluminum electrodes, for example.) There is an every-other-year conference known as ISDEIV, for International Symposium on Discharge and Electrical Insulation in Vacuum. The proceedings of these meetings contains lots of current information. The most recent of these meetings was in July, 2002 in France (see http://www.vide.org/isdeiv/isdeiv.html). Finally, there is a wealth of information in the IEEE Transactions on Electrical Insulation.

Polarity Switches

Polarity switches are necessary to allow injecting protons into the antiproton helix, and to support operations with different injection and collision helix configurations. The number presently available is too small, and construction (or procurement) of additional switches is necessary.

We were made aware of only one switch failure. When I inquired if in general these switches were trouble-free other than this one failure, I was told that there were "several" design modifications in the works for the new switches. No mention was made of any voltage limitations of the present (or improved) design switches, but if it is planned to operate in the future with higher voltages, the switches should be able to operate at these voltages. It may even be necessary to retrofit the existing switches to operate at higher voltages.

I would strongly recommend that procurement, rather than in-house manufacture, of these switches be explored. The Ross Engineering Corp, in Campbell, CA, has a great deal of experience in building high voltage switches and measurement equipment to voltages well above those of the separators. I have procured switches operating at comparable voltages from them at prices much below the cost for the in-house switches. Of course, a switch needs a safety housing, redundant interlocks, etc., but these do not have to be exceptionally costly. I could imagine asking the Ross people to build to a Fermilab print, or, perhaps even better, to design and build to a Fermilab specification. The new switched should be rated to function at the highest anticipated separator voltages. Oil-filling would allow a very compact design switch at the highest voltages discussed (which I mention because at one point space constraints were mentioned).

Beam Dynamics

My knowledge and experience in beam dynamics is much less than others at the review. However, it seemed clear to me that the situation with the setup and operation of the helix in its various configurations is not well understood. This is compounded by the fact that orbits, tunes, chromaticities, etc., change with time in ways, and for reasons, not understood. The entire problem is quite complex, with a number of phenomena contributing. And, it certainly seems that the state of knowledge is changing with time as well. The complete picture was too complex for me to follow well during the short time we had, even after reading the material sent before the review. It seems to me that devoting effort toward making some clear order regarding what is and is not known, what information is required to complete the understanding of various phenomena, and what is required to gain this information in terms of people and time on the accelerator, might be useful in providing guidance about the next steps.

Conducting accelerator physics measurements on the machine is in direct conflict with conducting the experimental program. And, since the accelerator performance is lower than originally planned, the experimenters are unlikely to willingly give up time to explore the accelerator physics, even if they might profit in the long term by so doing. In this situation, it may take strong intervention by laboratory management to reach (or enforce) an accord guaranteeing a certain level of accelerator physics time for specified measurements. If a clear, well-defined accelerator physics program can be presented, it makes the justification for such measures that much easier. Having clearly defined accelerator programs, prepared for in advance, also makes life more tolerable for the apparently very limited accelerator staff. And lastly, it can make future reviews easier and more productive.

<u>Further remarks by Sinclair</u> in additional e mail

I do not really have a good feeling that the separator people understand the origin of separator failures. "Sparking" is not necessarily an adequate term to describe what is going on. The feedthroughs and ceramic insulators bother me a bit (though we did not see enough of the feedthrough design to make any judgments). But, whether "sparking" in the sense of an arc between the two plates is the major cause of problems is not clear to me. Admittedly it is not an easy problem to deal with, since there can be several things going on, each of which may have a similar signature to the present instrumentation. I do not know how much time is available to work on this problem, but I would personally be inclined to build small test setups to evaluate the performance of each element of the problem - e.g. feedthroughs, ceramic standoffs, and the plates themselves (including materials, processing methods, etc.). I strongly feel that if processing to such a modest voltage as 130 kV/plate is requiring many weeks, one should simply stop and figure out what is wrong. I would think that a separator should process in days, not weeks.

6. Figures from Review- (reference material)

Helix Generation & Manipulation

Electrostatic Separators			
Horizontal		Vertical	
Site	# of Modules	Site	# of Modules
		A17	1
A49	1	A49	2
B11	2	B11	1
B17	4		
		C17	4
C49	1	C49	2
D11	2	D11	1
D48	1		

- 22 modules total with 12 separate power supplies.
- Electrode length of 101.25" per module.
- Maximum gradients of ~40 kV/cm (100kV per plate & a 50mm gap).
  $\Rightarrow$ ~10-11 μrad kick / module at 1 TeV.

- Injection : B17 & C17 dominate in controlling orbits through the F0 Lambertson & in providing separation through the arcs.
- Collision : Separators are ganged as 3-bumps to maintain arc separation:
  B0 → C0 → D0 : B11H – B17H – C49H
  B11V – C17V – C49V
  D0 → E0 → F0 → A0 → B0 : D11H – D48H – A49H
  D11V – A17V – A49V

Fig 2. Johnstone 8/14/03 Present Configuration

Separator Gradients (kV/cm)					
Horizontal			Vertical		
A49	1	40.000	A49	2	-40.000
B11	2	40.000	B11	1	40.000
B17	4	-19.042			
			B48	2	20.919
			C17	4	-27.906
C49	1	37.070	C49	2	40.000
D11	2	-40.000	D11	1	40.000
			D17	2	-34.381
A0U	1	5.897			
A17	1	-20.857	A17	1	-30.912

Table 4. Improved separator configuration using 6 additional arc modules.

Fig 3. Johnstone 8/14/03 Configuration with additional modules.

- Longer IR Separators: The Run II IR optics are different than those of Run I, and the Q1 quadrupoles (located between the outboard end of the A4, B1, C4, D1 separators & the arc dipoles) are unnecessary.
- Removing the Q1 magnets frees ~73" of space. Replacing the accompanying P spool with a shorter H spool yields an additional ~6". The 3 separator modules each side of the IP's could be extended by 24" beyond their existing ~101 length, with a corresponding increase in kick per given voltage.
- New separators need to be installed at both B0 & D0 to be useful.

Fig 4. Johnstone 8/14/03 Longer Separators at the IPs.

Cumulative Improvements

	Near-Misses Gain (%)	Ring-Wide Gain (%)
10% Separator Voltage Increase	10.0	10.0
50 μrad Half-Crossing Angle	21.5	0.5
Additional Arc Modules	11.4	19.9
Increased IR Separator Lengths	19.0	19.0
Total Separation Gain	**77.2 %**	**57.7 %**

Table 5. Beam separation improvements from modest helix upgrades.

Fig 5. Johnstone 8/14/03   Cumulative expected improvements

Alexahin (nominal emittance 15 pi mm mr, 95%?, or is it 20?)

We use as a figure of merit the so-called "radial separation"

$$S = \sqrt{\left(d_x / \sigma_x^{(\beta)}\right)^2 + \left(d_y / \sigma_y^{(\beta)}\right)^2}$$

where

$$\sigma_{x,y}^{(\beta)} = \sqrt{\beta_{x,y}\varepsilon_{\text{r.m.s.}}}$$

is the betatron part of the r.m.s. beam sizes

Johnstone

The rms beam extent in terms of the 95% emittance ε_{95}, and momentum spread δ_{95} is[2]:

$$\sigma(E) = \sqrt{\beta\varepsilon_{95}/6\gamma + (\eta\delta_{95}(E)/2)^2}$$

[1] Consult the complementary AP breakout talk by Y. Alexahin.

[2] All subsequent calculations assume $\varepsilon_{95} = 20\pi$ μm (normalized), and momentum spread δ_{95} = 14.E-4 (at 150 GeV).

Fig 6. Figures of merit used by Alexahin and Johnstone

Beam Studies

- Investigation of 18×18 operation with $18(p) \times 4(\bar{p})$.
- Lifetime, losses of pbars only (150Gev, ramp, 980 GeV).
  Dependence on: cogging location, chromaticities, emittances.
- Lifetime and losses of pbars with protons present.
  Dependence on: proton intensity, helix size, cogging location, tunes, chromaticity.
- Importance of nearest parasitics with a small crossing angle.

Fig. 7. Beam studies list of Sen

Status of Beam-beam effects

- **Injection**
  - Limit anti-proton lifetimes to under 10 hrs
  - No significant influence on protons
- **Ramp**
  - Cause about 10% anti-proton losses
    Anti-proton emittance growth during the ramp may be beam-beam related.
  - Not much influence on protons
- **Squeeze**
  - Anti-proton losses are low
  - Proton losses are occasionally vey high - causing quenches.
- **Collision**
  - Anti-proton and proton lifetimes not much affected by beam-beam at present intensities in good stores.
  - Occasionally have large emittance growth of anti-protons at start of store.
  - Proton losses (thought to beam-beam related) can sometimes be higher than acceptable

Fig. 8. Sen summary of beam- beam effects.

7. Attachments and References-

1. Agenda, Charge and Committee Members
2. Web Sites- http://www-bd.fnal.gov/run2upgrade/reviews/helix_Aug03.html

1. **Agenda, Charge and Committee Members**

Tevatron Helix and Separators Scope Review

Meeting: Tuesday, August 26, 2003
8:30 - 16:30 (Presentations: 9:00 - 15:00)
Venue: Huddle

Main reason for review:
What is the best long term plan for helix operation and separator improvements as the intensity of the pbar (and proton) bunches is increased?

[Scope Review (WBS 1.3.4.4.5.3)Decision on creating additional space in the lattice and to build longer separators at the interaction regions.]

Charge:

1) Review the present status of the beam helix scheme and possible/proposed near-term improvements and studies

a. Present status
- Separator layout and operation
- Helix description at all stages of injection to store, and possible modifications with existing hardware
- Description of aperture used in sigma and mm, also transverse vs dispersion
- Dynamic aperture investigations, and comparison with aperture used
- Beam correction and differential correction schemes

- b.Near-term improvements and studies
  - new helix up the ramp, no polarity reversal for roman pots, collimators
  - higher gradient operation (for short times), 18x18 study, crossing angle at interaction points, smaller beta* ~25cm
  - studies to include summary of studies so far, study plans and time needed in future

2) Review potential long-term improvements - Where new separators could go, what would need to be done, what modifications to existing hardware. What are the perceived benefits, relative effort and risk. Is the schedule reasonable?

3) Review and comment on possible gains from improvements.

4) Comment on the technical plan for increasing the separators gradient. should this be part of the RunII Program or a separate R&D project?

5) Suggest other possible approaches. Is there a consistent intergrated approach?

Upcoming Project Decisions

9/1/03 - Pursue additional and/or longer separators? Understand impact on other hardware, etc., that would need to be removed, relocated or modified.

4/28/04 - Pursue higher voltage operation and/or continue R&D

Agenda

08:30 - Executive Session

09:00 - 15:00 Presentations
Vladimir Shiltsev - Intro/Charge (20')
Ron Moore - Project Overview (20')
Tanaji Sen - Dynamic Aperture (45')
Yuri Alexahin - Optimizing Helices with Current Separator Configuration (45')
John Johnstone - Future Helix Upgrades (45')
Bruce Hanna - Separator Operation and Impact of Additional and/or Longer Separators
Rodger Bossert - Fabrication of Separators and Polarity Switches (20')
Gennady Romanov - R&D Correction Schemes, Feed-down Circut Operation, Modifying Lattice at A0 Straight Section (30')
Ron Moore - Summary (15')

15:00 - 16:30 Executive Session

There will be a lunch break and coffee/stretch breaks.

Presentation time limits INCLUDE 5-10 minutes for questions/discussions.

Reviewers

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Documents:
Status of Work on Helix/Aperture (Y. Alexahin) presented at the July 2003 DOE review
Future Helix Upgrades (J. Johnstone) presented at the July 2003 DOE review
Future Helix Upgrades (J. Johnstone) Aug 14, 2003
Proton Losses during Acceleration in the Tevatron
New aspects of beam-beam phenomena in hadron colliders
Beam Losses at injection energy and during acceleration in the Tevatron

Experimental Studies of beam-beam effects in the Tevatron
Theoretical studies of beam-beam effects in the Tevatron at collision energy
Beam Separators Parts List & Drawings
Beam-beam Effects: Analysis, Simulations & Experiments
Tevatron Beam Separator Traveler

Report:

Outcome:

Project Personnel
Ron Moore - Project Manager
John Johnstone - Future Helix Upgrades
Yuri Alexahin - Optimize Separation with preasent separators
Bruce Hanna - Tevatron Polarity switches for separators, coating of separators
Gennady Romanov (TD) - R&D for coating of separator electrodes
Rodger Bossert (TD) - Fabrication of polarity switches and separators
Jim Walton (Tev Dept) - Separator and power supply expert; conditioning/commissioning separators

Contact: Pushpa Bhat